Appendix A to FAR 99-26

ENERGY INNOVATIONS SMALL GRANT (EISG) PROGRAM

FINAL REPORT

CATALYTIC STABILIZER FOR INDUSTRIAL GAS TURBINES

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Legal Notice

Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

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Abstract

The purpose of this project was to test the feasibility of an ultra-low NOx (less than 5 ppm) catalytic stabilizer for use in sustaining lean combustion of natural gas in both current and advanced industrial Dry Low NOx (DLN) gas turbines. More specifically, this catalytic stabilizer will replace existing pilot burners that create excessive NOx emissions.

This project involved the cooperation of Solar Turbines who is interested in exploring the use of this technology for its advanced industrial engine. PCI developed the catalytic stabilizer technology while Solar provided test support as well as prototype Taurus 70 injectors at no cost to the program.

After the design and analysis of several different stabilizer candidates, prototype configurations were fabricated to fit into the existing geometry of the Taurus 70 injector without major modification to the engine. First, the catalytic reactors for the stabilizer were separately tested for robustness and performance at atmospheric pressure at PCI. Once these tests were completed, the integrated assembly of the catalytic stabilizer and the injector was tested at atmospheric pressure at PCI for robustness, flame stability, and emissions. After satisfactory completion of these tests the integrated assembly was tested over several days at Solar Turbines' high pressure facility. During this high pressure testing, the integrated assembly displayed excellent robustness with no occurrences of either flashback or auto ignition. At the Taurus 70 baseload and half load conditions, the catalytic stabilizer operated without a preburner for natural gas, while producing low emissions. Most significantly, at baseload conditions, NOx and CO emissions were less than 5 ppm while showing no signs of combustion-induced pressure oscillations, thereby demonstrating the proof of concept for such catalytic stabilizer technology. The next development steps, outside of the CEC Pier Program, will be to test the catalytic stabilizer technology in a full-scale atmospheric-pressure engine test rig followed by actual engine testing in 2002.

Key Words:
Pilot, catalytic stabilizer, catalytic pilot, industrial gas turbines

Executive Summary

Introduction

Currently, Dry Low NOx (DLN) machines use pilot burners to stabilize combustion at all operating conditions (i.e. startup, part loads, baseload and transients). Although DLN pilots commonly burn only 2-5% of the fuel at baseload, they are still the source of significant NOx emissions (on the order of 50% or more of the total NOx) preventing the achievement of low emissions (less than 5ppm) for such DLN engines. This fact is crucial because increasing environmental concerns are challenging the U.S. power generation gas turbine industry to reduce NOx emissions below those achieved by advanced DLN technology.

This project tested the feasibility of a novel concept for an ultra-low NOx (less than 5 ppm) catalytic stabilizer to replace existing high-NOx pilot burners. The expectation is that this catalytic stabilizer will help reduce emissions from industrial gas turbines while performing the same combustor stabilizing functions at all operating conditions. The proposed stabilizer replaces the highest NOx-producing component (i.e. the conventional pilot) of a DLN system with an ultra-low NOx lean catalytic stabilizer. This all but eliminates NOx emissions formerly arising from the DLN pilot while allowing the catalytic stabilizer to be used more aggressively (i.e. directing a larger percentage of the total fuel to it), in turn minimizing the equivalence ratio of the main combustion zone and thereby further reducing overall NOx emissions.

The catalytic reactor – which is the core component of the catalytic stabilizer – is based on Precision Combustion Inc.'s proprietary reactor technology. This reactor technology can operate on natural gas at the relatively low exit temperatures of today's industrial gas turbine compressors.

Objectives

1. Determine whether PCI' s catalytic stabilizer technology will fit into Solar's existing Taurus 70 engine envelope without major modification.
2. Determine whether a pre-burner is required for catalytic stabilizer operation with natural gas.
3. Determine whether the integrated assembly of catalytic stabilizer and injector can deliver NOx and CO emissions < 5 ppm for operation on natural gas.
4. Determine whether the catalytic stabilizer will allow leaner operation of injector.
5. Assess the operation of the catalytic stabilizer at all the standard engine operating conditions.

Outcome

1. The catalytic stabilizer fits into the existing Taurus 70 engine without major modification to the injector.
2. No preburner is required for the operation of the catalytic stabilizer with natural gas. The catalytic stabilizer lit off at temperature around 355°C during high pressure testing of the catalytic stabilizer. The light off temperature is lower than the compressor discharge temperature of 435°C at baseload condition of T70 engine.

3. The integrated catalytic stabilizer and the Taurus 70 injector assembly delivered NOx and CO emissions below 5 ppm for operation on natural gas.
4. The catalytic stabilizer allowed leaner operation of the injector.
5. The catalytic stabilizer demonstrated variable-load operability. In addition, low emissions were obtained at both 100% and 50% load conditions.

Conclusions

The test results support the continued development of ultra-low NOx catalytic stabilizer technology for industrial gas turbines and validate potential operational benefits of this technology in a power generation gas turbine. Specifically:

1. We demonstrated that today's PCI's catalytic stabilizer technology will fit into an existing engine envelope without major modification to the engine (in fact, two different catalytic stabilizer configurations were fabricated and integrated with two Solar Taurus 70 injectors without major modifications).
2. This project demonstrated that the catalytic stabilizer technology is very robust. During several days of testing, the catalytic reactor was free from auto-ignition and flashback over a wide range of stabilizer fuel-air ratios and airflows.
3. The tests showed that no preburner is required for the operation of the catalytic stabilizer with natural gas from half load to base load operation of the Taurus 70 machine. The catalytic reactor maintained sufficient activity during testing at inlet air temperatures of 430°C (full load compressor discharge temperature) and 385°C (half load compressor discharge temperature).
4. The project demonstrated that sufficient catalytic activity may be achieved at both baseload and half load to maintain stable combustion.
5. The project demonstrated that leaner operation in the front end of the combustor may be achieved with the catalytic stabilizer. The results show that the catalytic stabilizer can achieve low emissions at a front end temperature of 3050°F at baseload. This front end temperature at baseload is lower than the current baseload front end temperature of the Taurus 70 engines. Lower front end temperature signifies leaner combustion.
6. The project successfully demonstrated NOx and CO emissions of less than 5 ppm for operation with natural gas at Taurus 70 baseload conditions for a single injector, tested at high pressure.

Recommendations

The next step in developing this technology is performance testing of the catalytic stabilizer technology in a Taurus 70 engine. To accomplish this, twelve (12) Taurus 70 injectors must each be equipped with a PCI catalytic stabilizers. These twelve catalytically-stabilized injectors will be installed in a backside-cooled annular liner and engine tested as the final proof-of-concept for this technology. Proof-of-concept at engine level is required for commercial consideration and acceptance by the gas turbine manufacturers. The following is a list of the remaining necessary tasks leading to the commercialization of the catalytic stabilizer technology in an existing Taurus 70 engine:

1. *Mechanical analysis of the catalytic stabilizer*: An analysis determining the stress caused by temperature gradients will need to be performed on the relevant components of the stabilizer. This analysis will identify any components that are at risk of failing before a total operational life of 8000 hrs is reached (a minimum life of 8000 hrs is required for all components). If any such components are considered at risk, their design will be modified accordingly.
2. *Design simplification of the catalytic stabilizer*: The mechanical analysis will also identify any manufacturability issues of components. Costs that might be considered prohibitive to the fabrication of cost competitive devices will be addressed. In addition, this analysis is intended to enable easier manufacturing of larger quantities of components.
3. *Establish operating procedure for startup and steady state operation of the catalytic stabilizer in the Taurus 70 engine*: Based on the single injector tests of the current project, the assembly of the Solar's T70 injector and catalytic pilot functions well at base load and 50% load for the Taurus 70 engine. After testing steady-state conditions at other loads in the single injector rig, PCI will need to determine the optimum fuel splits (e.g. stabilizer equivalence ratio, injector equivalence ratio and % of total fuel to stabilizer) and overall operation of the stabilizer/injector assembly over the entire startup schedule.
4. *Establish control procedures for the modified Taurus 70 combustor*: Based on the results from (3) above, the method and scheme for controlling fuel flows may be modified and optimized (e.g. controls software, control valves & fuel delivery system).
5. *Fabricate 12 injectors and 12 stabilizers*: A new set of twelve (12) catalytic stabilizers and injectors need to be fabricated – along with a backside cooled annular liner.
6. *Perform atmospheric pressure rig testing:* Atmospheric pressure rig testing of the twelve-injector/stabilizer system.
7. *Perform Engine testing:* Conduct engine testing at Solar Turbines.
8. *Perform Cost analysis*: Cost analysis for the manufacturing of catalytic stabilizers will need to be performed.

Benefits to California

This project has contributed to the Public Interest Energy Research (PIER) program objective of introducing clean and efficient combustion technology into the California economy. Through close involvement with Solar Turbines, a California based industrial gas turbine manufacturer, PCI has demonstrated emission benefits, raising Solar's interest in an engine test in 2002. This supports our acceleration toward commercialization possibilities in Solar's Taurus 70 engine. In doing so, PCI's catalytic stabilizer technology will give California such benefits as

1. *Air quality with cost savings*: The concept allows significant NO_x emissions improvement with respect to the existing state-of-the-art industrial turbine combustors. The additional cost of this combustion system enhancement per engine is expected to be relatively low, and could help power suppliers avoid significant treatment costs – as well as increase the life of components associated with DLN

technology. The ease of retrofit within a DLN combustor geometry may permit wider acceptance and installation in existing high emission engines. The combination of lower emissions (competitive with current emissions standards for large utility installations) in smaller power generation engines provides more flexibility in citing of production capacity facilitating even more opportunities for improvements in California air quality through both emissions savings and economic incentive to displace/replace higher emission products.

2. *Energy efficiency*: The catalytic stabilizer offers a significant increase in energy efficiency compared with aftertreatment and encourages replacement of older, less-efficient sources with modern, higher efficiency turbines.
3. *Global warming*: Natural gas combustion produces less CO_2 than alternative fossil fuel combustion. Furthermore, this technology may eliminate the need for SCR aftertreatment – treatment that can produce problematic ammonia slip thereby contributing to greenhouse gases. So, by promoting an increased gas turbine share of the power generation market, catalytic stabilizer technology helps advance California efforts to limit greenhouse gas emissions.
4. *Benefit to California gas turbine industry*: Currently, California industrial gas turbine manufacturers are losing world market share in the face of increasing European and Japanese competitive pressures (price and government subsidy). In addition tightening emissions regulations in both Japan and the U.S. virtually mandate SCR use. The industrial sized gas turbines (Solar Taurus 70) are not generally large enough to support the large additional capital costs associated with an after treatment technology such as SCR. Thus as the regulations tighten, only the very large combined cycle gas turbines get built because they can spread the SCR investment over more installed production capacity. Unless industrial sized gas turbines develop single digit NO_x technology, they face a long-term threat of being displaced by larger, more efficient 3 and 9 ppm NOx-capable combined cycle gas turbines. Catalytic stabilizer technology with DLN offers a chance to reverse this trend for California based and other US industrial gas turbine manufacturers.
5. *Retrofit Potential*: In addition to equipping new gas turbine engines with reliable, ultra-Low NOx catalytic technology, already-existing engines may also be readily retrofitted with this technology without major modification to the engine. This ability to retrofit current engines provides California with significant opportunities to economically meet ever-increasing environmental legislation.

Introduction

The purpose of the project was to demonstrate a proof of concept of a catalytic stabilizer for Solar Turbines' industrial engines. The objective was to replace the partially-premixed, pilots used in Solar's advanced and current industrial Dry Low NOx (DLN) engines with a catalytic stabilizer from Precision Combustion Inc. to achieve low emissions. This project primarily supports the Environmentally Preferred Advanced Generation PIER subject area.

To achieve minimized NOx emissions with adequate combustion stability, advanced DLN systems typically use a high fuel/air ratio combustion zone to stabilize the overall lean flame and achieve engine turndown of a combustor. In this approach, a lean reaction zone (which is very close to the lean limit) is stabilized – or "piloted" – by a relatively stable reaction zone (e.g. with a higher global fuel/air ratio or increased unmixedness in the stabilizing zone). In addition to providing stability at normal baseload operation, the pilot also provides similar stability for engine start-up, load ramping and fuel transfer operations. In such a piloted system, the high stability pilot zone burns only a small fraction of the fuel (e.g. 5-10%) but contributes a high fraction of NOx (e.g. 50% or more of the total NOx emissions). Though this type of fuel staging requires significant design skill – the payoff is large: the pilot burner or primary stage allows advanced DLN combustors to generally operate close to the overall lean limit, resulting in relatively low overall NOx, e.g. 15 - 25 ppm. Nevertheless, dependence on a high stability, high NOx pilot zone is proving to be a barrier to further NOx reductions.

The problem arises from the challenge faced by the U.S. power generation gas turbine industry to achieve lower NOx emissions than even advanced DLN technology can achieve – a challenge motivated by increasingly strict environmental regulations. This is leading to a rapidly increasing requirement for BACT aftertreatment systems such as SCR and SCONOx™ for new – and even existing – power generation machines. Such requirements raise capital and operating costs while impairing efficiency. In the case of utility-sized machines, the result is experienced in higher energy costs being passed on the consumer. In the case of distributed power machines (industrial gas turbines) in the less-than-25 MW range (especially less than 10 MW), the result usually makes such projects economically unfeasible, thereby preventing industrial use of a highly efficient power source. The economic cost is likely to climb much more as aftertreatment becomes required for older machines upon upgrade, adding substantially to the cost of upgrade and potentially freezing in place inefficient older models.

The ultra-low NOx catalytic stabilizer demonstrated during this project supports the commercial potential to support replacement of existing high-NOx pilot burners now used for start-up, turndown and stabilization of combustion in Dry Low NOx (DLN) industrial engines. PCI's catalytic stabilizer replaces this highest NOx emissions component of a DLN system with an ultra-low NOx lean catalytic burner also capable of minimizing the lean limit of the main combustion zone. This all but eliminates NOx emissions from the pilot while allowing the stabilizer to be used more aggressively (i.e. directing more of the total fuel to the stabilizer) in minimizing main combustion zone emissions (i.e. by allowing leaner main zone operation). The enhanced stability of the catalytic stabilizer itself provides an operational capacity for reducing overall combustion zone acoustics at leaner conditions and improving turndown.

The catalytic reactor – which is the core component of the catalytic stabilizer – is based upon Precision Combustion Inc.'s patented reactor technology. This reactor technology can operate at the relatively low inlet temperatures existing in gas turbines.

Shown in Figure 1 is a schematic of the premixed catalytic stabilizer and the main injector used in Solar's engines. The main fuel/air injector has its own swirler, which interacts with the catalytic stabilizer flow. The exit of the stabilizer may be specially tailored to produce favorable aerodynamics for this main/stabilizer interaction. The catalytic reactor shown in the center for the stabilizer replaces diffusion flame tube and fits into the existing combustor configuration without modification to the surrounding combustor geometry. A Taurus 70 engine consists of 12 such injector/stabilizer assemblies arranged in an annular fashion around an annular central liner.

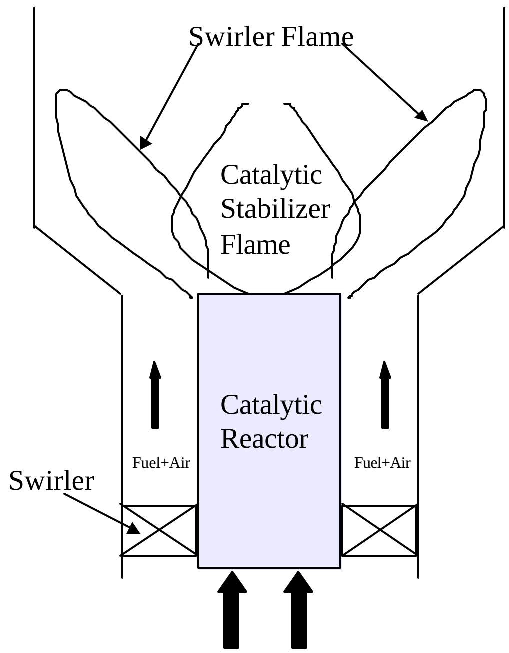

Figure 1:- Schematic showing the interaction between the premixed catalytic stabilizer and main injector

Project Objectives

The project objectives were similar to what had been specified in the proposal. Some of the objectives were either further tightened from the proposal or a quantitative value for a parameter was finalized which may have not been present in the initial proposal.

- Determine whether PCI's catalytic stabilizer technology will fit into existing Solar's Taurus 70 engine envelope without major modification.
- Determine whether a pre-burner is required for catalytic stabilizer operation on natural gas. In other words, assess whether PCI's catalytic reactor technology used for catalytic stabilizer can be operated on natural gas at baseload temperature of 430°C for Taurus 70 engine. The temperature limit of 430°C is the compressor discharge temperature of the Taurus 70 engine

at baseload. The catalytic stabilizer must be active at that temperature if it is not to require a preburner.

- Determine whether the integrated assembly of the stabilizer/injector can deliver NOx and CO emissions <5 ppm during operation on natural gas. The emissions criterion of NOx emission <5 ppm set forth for the project is more restrictive than the NOx criterion of <10 ppm proposed in our application. The reason for tightening the NOx criteria was to provide the engine manufacturer with enough confidence to guarantee 9 ppm NOx to its customer.
- Determine whether the catalytic stabilizer will allow leaner operation of the injector. The objective was to lower the current head-end temperature of the Taurus 70 combustor (note that a lower head-end temperature signifies leaner combustion).
- Assess the ability of the catalytic stabilizer to start-up the engine and operate at all loads. Emissions, however, are normally guaranteed from baseload down to 50% load in most engine applications.

Project Approach

The catalytic pilot/catalytic stabilizer development effort at PCI has been conducted under funding from CEC and DOE. To accomplish the project objectives, the following tasks were performed, with the second configuration of the catalytic stabilizer (mentioned below) being developed, fabricated, and tested under CEC funding.

<u>Task 1. Establish engine and stabilizer test conditions as well as the allowable physical envelope</u>

The primary goal of this task was to jointly (PCI and Solar Turbines) identify which Solar engine frame will benefit the most from PCI's catalytic stabilizer technology and then establish the physical dimensions required of the stabilizer in order to fit into the current injector. Both PCI and Solar mutually agreed to focus the catalytic stabilizer development on Solar's Taurus 70 engine. After identification of the engine, PCI received the load table for a typical Taurus70 engine (including a schedule for inlet temperature, pressure, air flow and fuel flow rates at different loads) as well as detailed drawings of a Taurus 70 engine. Table 1 shows the compressor discharge temperature and pressure (inlet conditions to the combustor), and pressure drop for the Taurus 70 machine (Hoshizaki, 1997)

Table 1- NOMINAL TAURUS 70 COMBUSTOR OPERATING CONDITIONS

Baseload Inlet Temperature	705 K (432^{o}C/810 ^{o}F)
Baseload Inlet Pressure	1.7 Mpa (250 psia)
Baseload Pressure Drop	4.0%
Halfload Inlet Temperature	636 K (363^{o}C/ 687 ^{o}F)
Halfload Inlet Pressure	1.02 Mpa (153 psia)
Halfload Pressure Drop	3.5%

This information allowed PCI to calculate flow functions for the engine and atmospheric pressure testing at PCI (this flow function must be maintained in order to maintain the proper Mach number within the combustor). During testing at atmospheric pressure under Task 5, all the conditions shown in Table 1 was maintained except the inlet pressure. As part of Task 1, PCI also estimated the amount of fuel and air flow rates required for the catalytic stabilizer and how these might be achieved without major modification to the injector. A larger fraction of both fuel and air would be used for the catalytic stabilizer than what were used by the standard pilot. Table 2 shows the percentage air-splits in the different section of the combustor for both the modified T70 injector with catalytic pilot and the Standard T70 injector. We observe that for the catalytic stabilizer configuration 12.2% of the air enters the stabilizer versus 3.3 percent for the pilot in the standard configuration.

Table 2- AIR SPLITS IN THE COMBUSTOR

Catalytic Stabilizer Configuration		**Standard Pilot Configuration**	
Catalytic Stabilizer	12.2%	Pilot	3.3%
Swirler	40.6%	Swirler	45.0%
Liner (dome cooling)	12.2%	Liner (dome cool.)	13.4%
Liner (dilution holes)	35.0%	Liner (dilution holes)	38.3%

Task 2. Design the several catalytic stabilizer candidates

In this task designs of several embodiments of the catalytic stabilizer were developed and analyzed to determine the feasibility of success, the fabrication difficulty, and potential fatal flaws. Of course, all design embodiments had to meet the constraint of fitting into the existing Taurus 70 injector envelope without major modifications. Based on the analysis – and to reduce the time involved in the development of catalytic stabilizer – two candidate designs were chosen. From hereon these two configurations will be referred to as Configuration 1 (developed, fabricated and tested under DOE funding) and Configuration 2. The catalytic reactor for Configuration 1 had a shorter reactor than that of Configuration 2. The detailed drawings for the fabrications of the two configurations were made only after they had been selected.

Task 3. Perform CFD studies of the catalytic stabilizer

In conjunction with Task 2, a Computational Fluid Dynamics (CFD) analysis was performed to reduce iterations in prototype manufacturing. FLUENT, a commercially available CFD code, was used. FLUENT was used to evaluate the mixing of fuel and air for the reactor in the stabilizer. Several designs for the premixer were investigated and the design that gave best mixing was chosen. The mixing goal was to achieve an unmixedness of less than 5% for the fuel and air mixture entering the catalytic reactor of the stabilizer. Although the reactor can handle higher levels of unmixedness, a tighter tolerance was used for this parameter to avoid any NOx penalty. This optimized premixer design identified through FLUENT was used for both versions of the catalytic stabilizer. Experimental testing during Task 5 supported the qualitative prediction of good mixing at the inlet of the reactor by. FLUENT.

Task 4. Fabrication and of the catalytic stabilizer

In this task the two configurations of the catalytic stabilizer were fabricated. All the components of the stabilizers were fabricated at Precision Combustion. However, a few of the components were sent to vendors for laser drilling and wire EDM (electrical discharge machining). Catalytic elements for the catalytic reactor were coated with catalytic materials and then integrated with the reactor housing. Both configurations were then integrated into the Taurus 70 injectors. The Taurus 70 injectors were supplied at no cost to the program by Solar Turbines.

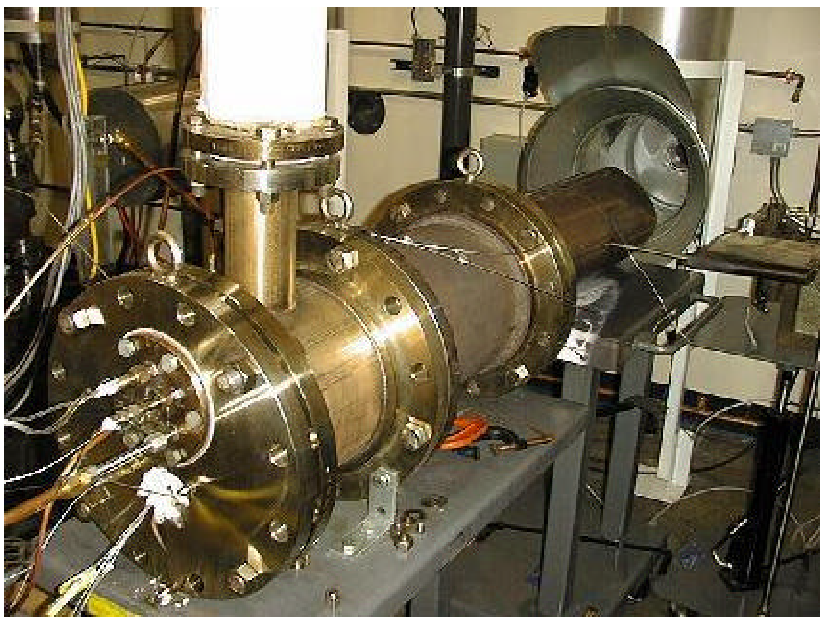

Figure 2:- Picture of the Pilot Testing Rig at PCI

In addition to fabrication of the catalytic stabilizers, a testway , which is shown in Figure 2, was modified to permit testing of the fully-integrated stabilizer/injector assembly at atmospheric conditions. For this purpose several flanges were fabricated to hold the assembly in the rig. Fuel and air supplies were plumbed to deliver the necessary fuel and air so that the aforementioned engine flow function can be matched and maintained.

Task 5. Full-scale, atmospheric pressure testing of the stabilizer at PCI & Task 6. Analysis of results

In this task both configurations were tested at PCI – with the catalytic reactor alone as well as integrated with the injector. First, fuel/air mixing in the premixer of the stabilizer was measured to validate CFD prediction. At the inlet of the reactor, samples were drawn for gas analysis at the same axial and radial position but different circumferential positions. Gas analysis by gas chromatography showed that deviation from the average was less than 5%. This measurement of small deviation is in excellent agreement with the CFD prediction for deviation. After completing the mixing tests, both catalytic reactors were tested for reaction performance. The catalytic reactors lit off at nearly the same temperature for a given inlet air and fuel mixture. For both configurations, the temperatures of the catalytic elements were sufficiently below those limits set for durability.

After completing the testing for the catalytic reactors, the two different configurations were then integrated with Taurus 70 injectors and tested. Since the testing was conducted at atmospheric pressure, flow function, inlet air temperature, and the pressure drop similar to baseload conditions were maintained. During this portion of testing we discovered that the reactor T/C's as well as the gas analysis probes were affecting the stabilizer's performance. Due to this interference we had to re-instrument the catalytic stabilizer assembly.

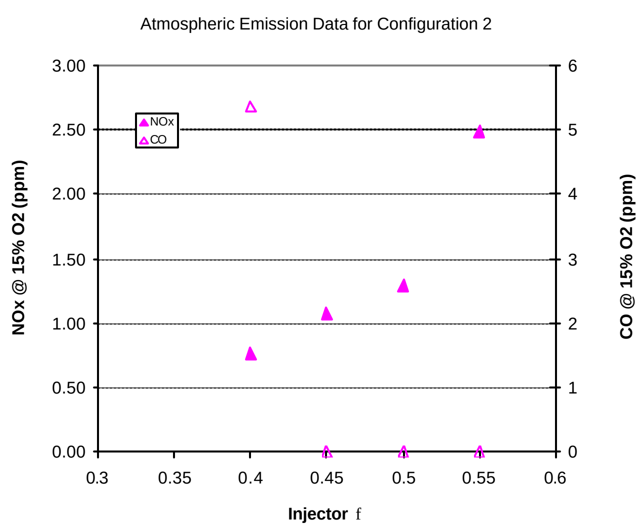

Figure 3:- NOx and CO results from atmospheric pressure testing of the modified T70 injector

After correcting this, emission measurements were obtained for different stabilizer and injector equivalence ratios. For both stabilizer configurations lean combustion could be sustained in the main injector. Figure 3 shows emission data obtained for Configuration 2 at atmospheric pressure condition as a function of natural gas equivalence ratios in the injector for a constant stabilizer equivalence ratio of 0.5. From this Figure we observe that injector operation could be sustained to an equivalence ratio of 0.4 and for the range of equivalence ratios shown in Figure 3, the NOx emission was below 5 ppm

To summarize, atmospheric testing of the catalytic stabilizer with the main-injector showed that the catalytic reactor was active and operating within durability guidelines. In addition, NO_x and CO emissions were very low for both 50% and 100% load conditions. Thus we felt confident in performing the next Task: testing the catalytic stabilizer at Solar's full pressure injector rig.

Task 7. Full scale, high pressure testing with Taurus 70 Injector

The objectives of this testing were to determine the operating temperature required for the catalytic reactors, to determine the durability and robustness of the catalytic reactor, to determine the performance of the catalytic reactors at high pressure and, finally, to determine the emissions and acoustics at baseload conditions for the integrated catalytic stabilizer and injector assembly.

Both stabilizer configurations were tested at Taurus 70 baseload conditions for operation with natural gas. The tests were conducted in Solar's Single Injector High-pressure Facility. The objectives of this testing were to determine the operating temperature required for operation on natural gas, to determine the durability and robustness of the catalytic reactor, to determine the performance of the catalytic reactors at high pressure and, finally, to determine the emissions and acoustics at baseload conditions for the integrated catalytic stabilizer and injector assembly.

All emission results will be discussed in terms of pilot and swirler equivalence ratios and front end adiabatic flame temperatures (calculated based on pilot and swirler air and fuel flow) rather than primary zone flame temperatures, which are difficult to measure because of entrainment of dome cooling air and liner dilution air.

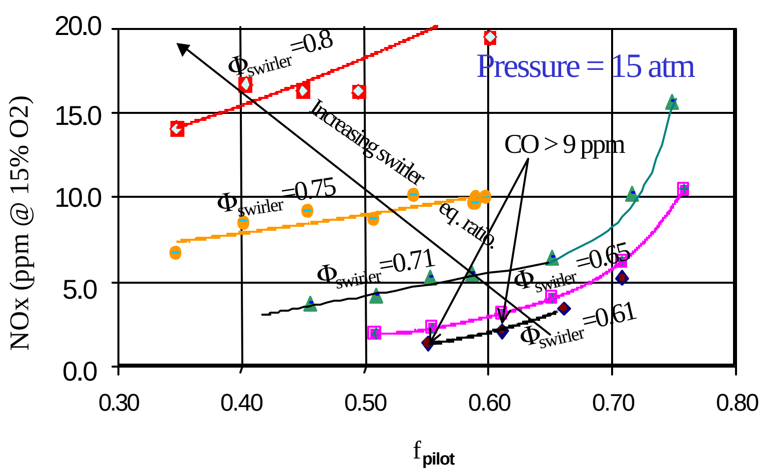

Figure 4:- NOx emission dependence on catalytic pilot equivalence ratio

Figure 4 shows the sensitivity of NOx emission data obtained to catalytic pilot equivalence ratios at a pressure of 15 atmosphere during operation on natural gas for configuration 2. The symbols show the experimental data obtained after correction to 15% O2 in a dry sample, and the lines represent trend lines drawn through the data points with constant swirler equivalence ratio. These group of data will be referred as "Data from Day 1 testing". For a constant swirler equivalence ratio ($\phi_{swirler}$), emission data were first collected with the highest pilot equivalence ratio (NOx< 20). Then gradually the pilot equivalence ratio (ϕ_{pilot}) was dropped until blow-off occurred or CO exceeded 20 ppm. CO exceeded 10 ppm in only the first two data points

(ϕ_{pilot}=0.55, 0.61) from the lowest swirler equivalence ($\phi_{swirler}$ = 0.61) ratio series shown in Figure 4. CO was lower than 10 ppm at all other data points shown in Figure 4.

We observe from this figure that for higher swirler equivalence ratios less piloting is necessary and blowoff occurred at lower pilot equivalence ratios. This is expected and the increased stability is achieved at the expense of higher NOx emission. Below ϕ of 0.65, NOx dependence on the pilot equivalence ratio was linear.

Figure 4 also shows that the best NOx emission (NOx < 5 ppm) can be obtained for this configuration of modified Taurus 70 injector, when the swirler equivalence ratio is in the range of 0.5 to 0.65 and the pilot equivalence ratio is in the range of 0.55 to 0.65. Thus the modified injector showed a wide operability range. If the fuel to the catalytic pilot was shut-off while operating at these low swirler equivalence ratios (0.6-0.65), blow-off would occur. This indicated that the catalytic pilot provided stability to the main flame.

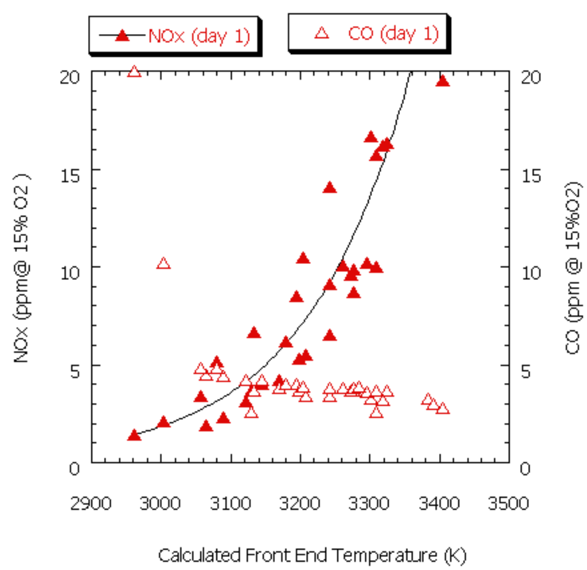

Figure 5:- Measured NOx and CO emission for the modified Taurus 70 injector at close to 100% load condition

Figure 5 shows the same emission data (CO and NOx) of Figure 4 when plotted as a function of front end temperature of the combustor. The front end temperature was calculated based on the air flows to the pilot, and injector, and fuel flows to the swirler and pilot. Note that the calculated front end temperature does not take into account any reverse flow dilution air (liner cooling) or dome cooling that may participate in the combustion process occurring in the primary zone of the combustor. As such, the temperature shown in the x-axis is not the primary zone temperature during combustion.

The symbols represent measured emission data (closed symbols represent NOx data and open symbol represents CO data) after correction and the solid line is an exponential trend line drawn through the NOx data set. Figure 5 also shows the emission at the modified operating temperature of approximately 3050 ^{o}F (1677 ^{o}C/ 1950 K) for this modified configuration at 100% load to be around).

We observe that with this modified configuration less than 5 ppm NOx was achieved for the operating condition. Also, less than 5 ppm NOx was also achieved in the front end temperature range of 3000- 3150 ^{o}F (1627-1732 ^{o}C/1900 – 2005 K). In T70 injector test with standard pilot with a similar (same effective area) swirler, NOx emission of 15 ppm resulted for an operating front end temperature of approximately 3400 ^{o}F (1868 ^{o}C/2140 K). Clearly, the use of larger air split for the catalytic pilot, - can be observed from flow-splits shown in Table 2, - has permitted operating at lower front end operating temperature and thereby decreased NOx.

Figure 5 also shows that at front end temperature of approximately 3070 ^{o}F (1687 ^{o}C/1960 K), measured NOx values of 1.9 ppm and 5.2 ppm were observed. This scattering in NOx data is due to the use of very different pilot and swirler equivalence ratios for the two cases. If these data are compared to the data of Figure 4, it can be observed that a NOx level of 1.9 ppm was observed for swirler and pilot equivalence ratios of 0.61 and 0.66 respectively, whereas for the higher NOx case swirler and pilot equivalence ratios were 0.61 and 0.71 respectively. The use of a higher pilot equivalence ratio was responsible for the increase in NOx. These data shows that there is an optimum percent of pilot fuel flow above which increasing the percentage has detrimental effect on NOx emission.

Thus NOx and CO emissions are not a single valued function of the calculated front end temperature. Depending on the pilot and swirler equivalence ratios, these emissions can be different at the same calculated front end temperature. Figure 5 thus in combination with Figure 4 help to identify the optimum operational space in terms of swirler and pilot equivalence ratios for lowest emissions.

Figure 6 shows the measured combustion driven pressure oscillation during testing of configuration 2 at baseload condition. We observe the pressure oscillation were low in the temperature range of 3025 ^{o}F- 3200 ^{o}F (1662 ^{o}C-1760 ^{o}C/1935- 2033 K)

Task 8 Final Report

The results of Task 1 to Task 7 are presented in this report along with conclusions and suggestions for future work. The results obtained during high pressure testing at Solar are also given in this report.

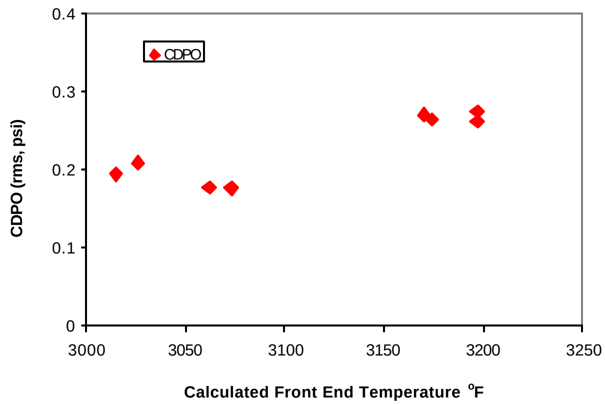

Figure 6:- Measured CDPO at baseload conditions

Project Outcomes

- *Catalytic stabilizer developed for the Taurus70 injector fits into the existing geometry*

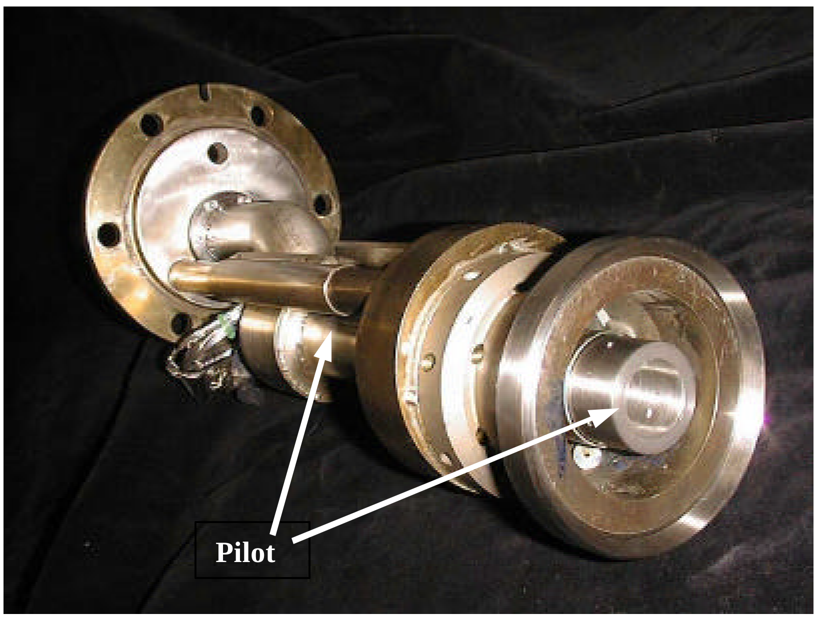

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Figure 7:- Photograph of modified Solar Taurus 70 premixed fuel/air injector hardware, with PCI's catalytic stabilizer installed on the injector centerline (within the swirler hub). Orientation of the injector in the photograph shows the mounting flange at upper left, and the swirler and catalytic reactor exits at lower right

The catalytic stabilizers fabricated during this project fit within the swirler hub of the standard injector without any major modification. Figure 7 shows a picture of the stabilizer hardware integrated with the injector hardware

- *No preburner is required for the catalytic stabilizer operation on natural gas. Reactor lit off at temperatures lower than the temperature of the compressor discharged air at baseload for Taurus 70 engine.*

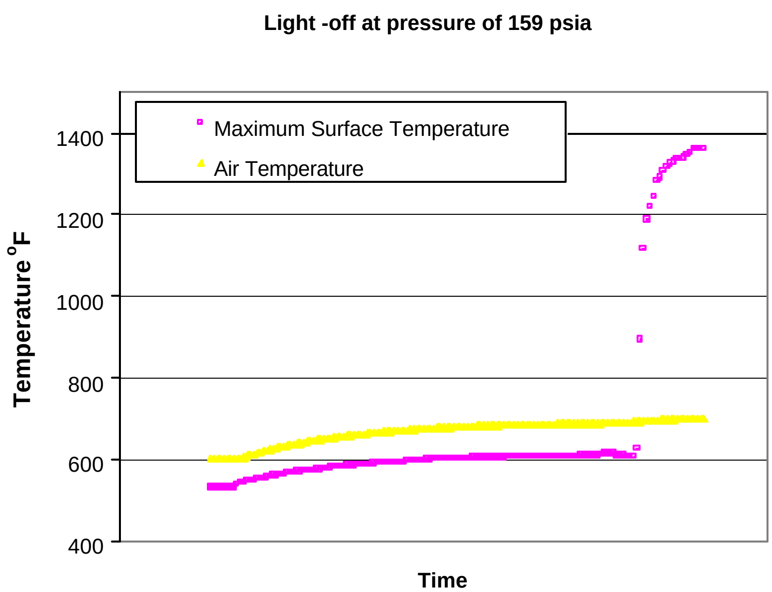

Figure 8:- Light-off data for the catalytic stabilizer at a pressure of 159 psia

Figure 8 shows a typical lightoff curve for Configuration 1 (the lightoff characteristics of Configuration 2 are similar) during operation on natural gas (CH_4: 95.82%, C_2H_6: 1.8%, C_3H_8: 0.32%, C_4H_{10}: 0.13%, CO_2: 0.89%, N_2: 1.0) at Solar Turbines' facility. This plot shows the temperature of combustor inlet air, the surface temperature at a distance of 0.125" from the start of the catalyst section, and the maximum surface temperature – all as functions of time. The combustor inlet air temperature was approximately 670°F (355°C) and the initial surface temperature about 580°F (305°C) when catalyst light off occurred. This air temperature of 670°F is lower than the compressor discharged air temperature of 725°F (385°C) at 50% load. From this data we can conclude that the catalytic reactor of the stabilizer will be active without a preburner even during half load operation of the machine.

- *Achieved robust and durable operation of the catalytic stabilizer. No flashback or autoignition.*

During the several days of operation no autoignition or flashback in the stabilizer was observed. Once the reactor was lit off, the maximum temperature that was reached on the catalyst surface was similar to that observed during atmospheric pressure testing at PCI. This temperature was well below material specifications to meet a minimum of 8000 hours durability.

- *The integrated catalytic stabilizer and injector achieved NOx and CO emission < 5 ppm during single injector testing at a high pressure facility of Solar*

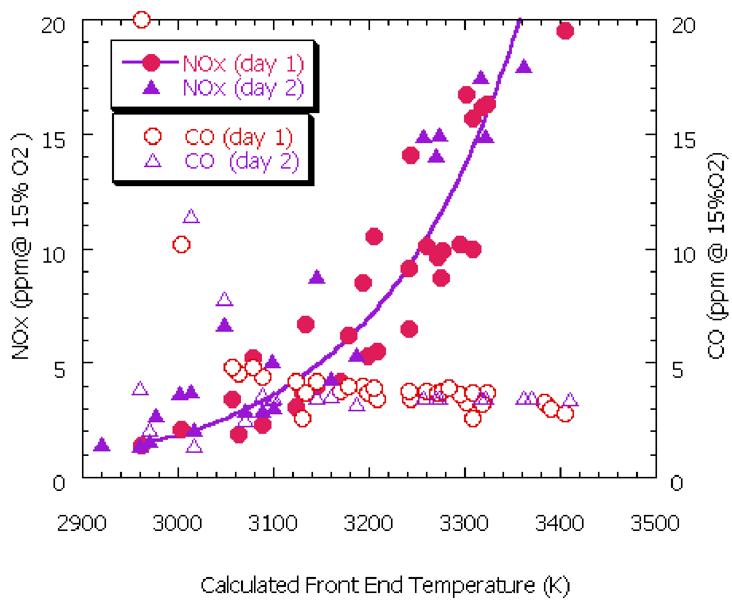

Figure 9:- Oxygen-corrected NOx and CO emissions vs. calculated front-end temperature

Figure 9 shows the base load emissions data obtained during the testing of a single injector integrated with a catalytic stabilizer at Solar's high-pressure facility on two different days. The x-axis shows the calculated front-end (head-end) temperature with the y-axes showing corrected emissions (left axis for NOx and the right for CO). Note that the calculated front end temperature does not take into account any reverse-flow dilution air or dome cooling that may participate in the combustion process. As a result, the calculated adiabatic front end temperature is higher than the actual head-end temperature. The solid symbols (circles represent the 1st day data; triangles the 2nd day) denote NOx data whereas the open symbols denote CO data. The solid line is a exponential fit for 1st-day NOx data. The scattering in the NOx and CO data is discussed in the section that describes Task 7. Both CO and NOx emissions of less than 5 ppm can be achieved over the head-end temperature range of 3000- 3150 ^{o}F (1627-1732 ^{o}C/1900 – 2005 K) and emissions of less than 10 ppm can be achieved in the range of 3000°F to 3250°F (1627-1787 ^{o}C/1900-2060 K).

If we take an operating front end temperature at baseload of 3050°F, we can see that the emissions at this temperature are below 5 ppm (though the actual engine baseload front end flame temperature must be kept significantly higher – through the strategic use of combustion system air distribution – due to stability issues, the catalytic stabilizer allows a much lower flame temperature while maintaining both the overall firing temperature and stable combustion). The integrated assembly also has a wide operability range over which low emissions are achieved. This operability is crucial for field implementation of the technology.

- *Catalytic stabilizer is targeted toward leaner operation of the injector*

The targeted front end temperature at baseload for this configuration was 3050 °F, which – as stated earlier – is considerably lower than the baseload temperature of the current Taurus 70 engines in the field. A lower baseload head-end temperature signifies leaner stabilization of the injector with lower NOx.

- *Catalytic stabilizer delivered low emissions at 50% load conditions*

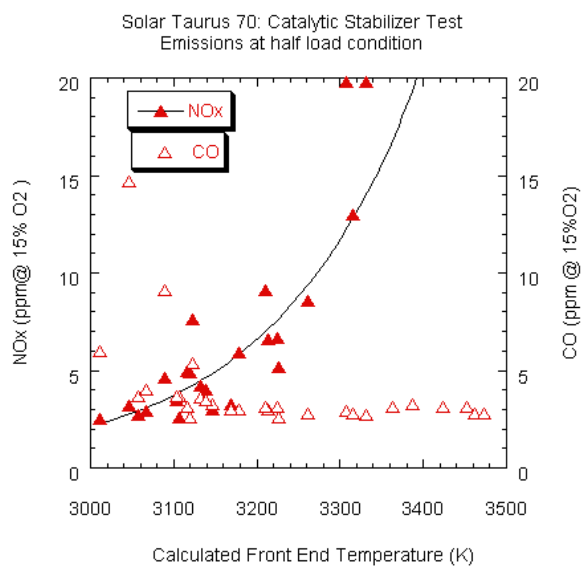

Figure 10:- NOx emissions at 50% load conditions from the single injector/catalytic stabilizer assembly testing

Figure 10 shows NOx data obtained during integrated single injector/catalytic reactor test at 50% load condition of the Taurus 70 engine. In the head-end temperature range of 3000°F – 3150°F, NOx emissions below 5 ppm and CO emission below 10 ppm were achieved. Once again, due to air cooling flows (dilution, dome, etc.) the actual temperature in the primary zone is lower than that presented in the figure. The fact that the stabilizer can operate at 50% and base loads provides enough confidence to conclude that this level of emission can be achieved between 50%-100% load for T-70 engine. At 50% load the compressor discharge temperature will be high enough to sustain catalytic activity allowing the stabilizer to be used to stabilize combustion from 50% to base load.

Conclusions and Recommendations

- The test results support the continued development and efforts to commercialize catalytic stabilizer technology as ultra-low NOx technology for industrial gas turbines.
- We demonstrated that PCI's catalytic stabilizer technology will fit into existing T-70 engine envelope without major modification to the engine. Two different catalytic stabilizer configurations were fabricated and integrated with the Taurus 70 injector without major modifications.
- The project demonstrated that the catalytic stabilizer technology is significantly robust: during several days of testing the catalytic reactor was free from auto-ignition and flashback even with wide variation of fuel-air ratio and airflow to the stabilizer
- The tests show that no preburner is required for the operation of catalytic stabilizer technology from half load to base load operation of Taurus 70 machine. The catalytic reactor maintained sufficient activity during testing at inlet air temperatures of 430°C (full load compressor discharge temperature) and 385°C (half load compressor discharge temperature).
- The project demonstrated that sufficient catalytic activity can be achieved both at baseload and half load to achieve stable combustion.
- The project demonstrated that leaner operation in the head-end of the combustor can be achieved with the catalytic stabilizer. In addition, the catalytic stabilizer can achieve low emissions at a head-end temperature of 3050°F. This calculated front end temperature is lower than the front end temperature currently achievable in the Taurus 70 engine at baseload. The current field limitations are due to combustion instability of the current Solar's combustor. However, the catalytic stabilizer will allow combustor inlet air to be diverted from cooling and dilution air to the head-end. Lower front-end temperature signifies leaner combustion.
- The project successfully demonstrated NOx and CO emissions less 5 ppm at baseload conditions of Taurus 70 injector for a single injector at high pressure.

The next step in developing this technology is a performance test of the catalytic stabilizer in a Taurus 70 engine. To accomplish this, twelve (12) Taurus 70 injectors must each be integrated with a PCI catalytic stabilizer. These twelve catalytically-stabilized injectors will be installed in a backside-cooled annular liner. This engine test will be the final proof-of-concept for this technology and is a required step in the Solar's path to technology commercialization in their industrial engines. Additional funding will be required to conduct the following:

1. _Mechanical analysis of the catalytic stabilizer_: An analysis determining the stress caused by temperature gradients will need to be performed on the relevant components of the stabilizer. This analysis will identify any components, which are at risk of failing before a total operational life of 8000 hrs is reached (a minimum life of 8000 hrs is required for all components). If any such components are considered at risk, their design will be modified accordingly.
2. _Design simplification of the catalytic stabilizer_: The mechanical analysis will also identify any manufacturability issues of components. Costs that might be considered

prohibitive to the fabrication of cost competitive devices will be addressed. In addition, this analysis is intended to enable easier manufacturing of larger quantities of components.

3. *Establish operating procedure for startup and steady state operation of the catalytic stabilizer in the Taurus 70 engine*: Based on the single injector tests of the current project, the assembly functions well at base load and 50% load for the Taurus 70 engine. After testing steady-state conditions at other loads in the single injector rig, PCI will need to determine the optimum fuel splits (e.g. stabilizer equivalence ratio, injector equivalence ratio and % of total fuel to stabilizer) and overall operation of the stabilizer/injector assembly over the entire startup schedule.
4. *Establish control procedures for the modified Taurus 70 combustor*: Based on the results from (3) above, the method and scheme for controlling fuel flows may be modified and optimized (e.g. controls software, control valves & fuel delivery system).
5. *Fabricate 12 injectors and 12 stabilizers*: A new set of twelve (12) catalytic stabilizers and injectors need to be fabricated – along with a backside cooled annular liner.
6. *Perform atmospheric pressure rig testing:* Atmospheric pressure rig testing of the twelve-injector/stabilizer system.
7. *Perform Engine testing:* Conduct engine testing at Solar Turbines.
8. *Perform Cost analysis*: Cost analysis for the manufacturing of catalytic stabilizers will need to be performed.

Public Benefit to California

This project has contributed to the Public Interest Energy Research (PIER) program objective of introducing clean and efficient combustion technology into the California economy. Through close involvement with Solar Turbines, a California based industrial gas turbine manufacturer, PCI has demonstrated emission benefits, raised Solar's interest in an engine test in 2002, which supports catalytic pilot's acceleration toward commercialization possibilities in Solar's Taurus 70 engine. In doing so, PCI's catalytic stabilizer technology will give California such benefits as

1. *Air quality with cost savings*: The concept allows significant NO_x emissions improvement with respect to the existing state-of-the-art industrial turbine combustors. The additional cost of this combustion system enhancement per engine is expected to be relatively low, and could help power suppliers avoid significant aftertreatment costs – as well as increase the life of components associated with DLN technology. The ease of retrofit within a DLN combustor geometry may permit wider acceptance and installation in existing high emission engines. The combination of lower emissions (competitive with current emissions standards for large utility installations) in smaller power generation engines provides more flexibility in citing of production capacity facilitating even more opportunities for improvements in California air quality through both emissions savings and economic incentive to displace/replace higher emission products.
2. *Energy efficiency*: The catalytic stabilizer offers a significant increase in energy efficiency compared with aftertreatment and encourages replacement of older, less-efficient sources with modern, higher efficiency turbines.
3. *Global warming*: Natural gas combustion produces less CO_2 than alternative fossil fuel combustion. Furthermore, this technology may eliminate the need for SCR

aftertreatment – treatment that can produce problematic ammonia slip thereby contributing to greenhouse gases. So, by promoting an increased gas turbine share of the power generation market, catalytic stabilizer technology helps advance California efforts to limit greenhouse gas emissions.

4. *<u>Benefit to California gas turbine industry</u>*: Currently, California industrial gas turbine manufacturers are losing world market share in the face of increasing European and Japanese competitive pressures (price and government subsidy). In addition tightening emissions regulations in both Japan and the U.S. virtually mandate SCR use. The industrial sized gas turbines (Solar Taurus 70) are not generally large enough to support the large additional capital costs associated with an after treatment technology such as SCR. Thus as the regulations tighten, only the very large combined cycle gas turbines get built because they can spread the SCR investment over more installed production capacity. Unless industrial sized gas turbines develop single digit NO_x technology, they face a long-term threat of being displaced by larger, more efficient 3 and 9 ppm NOx-capable combined cycle gas turbines. Catalytic stabilizer technology with DLN offers a chance to reverse this trend for California based and other US industrial gas turbine manufacturers.
5. *<u>Retrofit Potential</u>*: In addition to equipping new gas turbine engines with reliable, ultra-Low NOx catalytic technology, already-existing engines may also be readily retrofitted with this technology without major modification to the engine. This ability to retrofit current engines provides California with significant opportunities to economically meet ever-increasing environmental legislation.

Development Stage Assessment

The Development Assessment Matrix below indicates that PCI has progressed through Stage 6 with Marketing and Engineering /Technical activities are they relate to the PCI catalytic stabilizer technology embodied in an actual device that fits within a commercial Solar Taurus 70 industrial gas turbine. Much of the Marketing and Business Assessment activities have been covered by PCI in the development of a Business Plan for Clean Turbine Systems, a manufacturing business venture proposed by PCI to a DOE CAP audience in May 2000 to develop the PCI catalytic combustor manufacturing capacity. A copy of that Plan is included in the Appendix to this report.

We address the Contractual as well as Strategic (includes licensing and manufacturing) in the Clean Turbines Business Plan as well. An assessment of those categories listed below does indicate that PCI is through Stage 3 in all areas.